

THE DYNAMICS OF WET PRESSING

Project 3258

**Report One
A Progress Report
to**

MEMBERS OF THE INSTITUTE OF PAPER CHEMISTRY

June 3, 1975

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

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THE DYNAMICS OF WET PRESSING

SUMMARY

The effectiveness of pressing wet paper in contact with a felt in a nip of two hard rolls at constant load and speed is dependent on the compressibility of the felt, the compressibility and permeability of the paper, the uniformity of compression, and the extent of rewetting. The paper is subject to compression under a pressure-time schedule primarily governed by the felt compressibility including a small effect of speed. If the flow of water in the paper is lateral, such as in a plain press with a saturated felt, the "midnip" moisture of the paper is controlled by the paper compressibility. The final dryness of the paper is somewhat less due to the lateral flow through the midnip and possibly rewetting. If the flow is transversal out of the paper, such as in a grooved or sleeved press, the midnip moisture is controlled by the paper permeability and basis weight. The higher the speed, the wetter is the paper. The final dryness of the paper is dependent on the extent of rewetting.

Rewetting is largely a matter of capillary suction. The source of the rewetting water is the grooves, holes, or meshes in a transversal-flow press and the lateral flow in the felt through the midnip in a lateral-flow press. The rate of rewetting is determined by the initial recovery and interfacial permeability of the paper, as well as the time during which the paper and the felt are in intimate contact. The higher the speed, the less is the rewetting.

The uniformity of compression is largely dependent on the felt structure, and to a lesser extent on the roll surface (land and open areas). The compression is less over the area of the paper which is not sufficiently supported by the felt

and the roll. Nonuniform compression can be alleviated to some extent by a thicker batt of the felt and a higher basis weight of the paper. Extreme loading tends to worsen the uniformity of compression, and possibly damage the felt fibers.

A plain press has the advantages of effective compression and little rewetting, but suffers from a low capacity in loading. Crushing is a consequence of the lateral flow reaching a critical velocity. A grooved or suction press possesses a large loading capacity, but inherits the drawbacks of nonuniform compression and a high rewetting potential.

If the present understanding of the pressing dynamics is basically correct, an ideal press system could be conceived as a single plain press with an extended nip, using a uniform and low-moisture felt as a water receptacle for transversal flow in the long nip, and operating at a moderate load and high speed. Such a development might reduce both capital costs by simplification of the pressing equipment and operating costs by energy savings in drying as well as in pressing (vacuum and friction).

INTRODUCTION

The chief function of a wet press in a paper machine is to express water from a continuous web of paper by mechanical compression. If paper were perfectly elastic, and water, inertialess, as well as inviscid, the web would attain a minimum moisture at the peak pressure, independent of speed. In reality, paper is viscoelastic, and exhibits significant time-dependent deformations. The important factor in pressing dynamics, however, is the resistance of the fiber structure under compression to the flow of water. The inertial effects, on the other hand, can usually be neglected. In expansion, the web may reabsorb water, resulting in a lower dryness than already attained. Further complications such as nonuniform compression, shadow marking, and web crushing, severely limit the dryness theoretically achievable. This review is intended to clarify the pressing operation on the basis of our present understanding with the aid of simple mathematical analyses. Citations of the literature, however, will be mostly omitted with apology.

COMPRESSION AND MIDNIP MOISTURE

When a wet web in contact with a partially saturated felt enters a press nip, the web soon reaches saturation provided air can escape. Further compression forces some water to flow out of the web into the unsaturated felt. The transversal flow of water past a fiber layer generates a drag force which compresses the layer, and a more compressed layer offers a higher resistance to flow. Thus, the dynamic state of the web is determined by the interaction of compression and flow. As a consequence, there exhibits a continuous decrease of hydraulic pressure in the saturated web in the direction of flow with a corresponding increase of apparent density toward the web-felt interface.

Further along the converging nip, the felt may also become saturated. The resistance of a felt to flow, usually an order-of-magnitude lower than that of paper, can be neglected for the moment. As the nip pressure continues to increase, the web becomes more dense, and the flow velocity first increases and then decreases until the point of minimum moisture is reached.

If transversal flow is not permitted, a part of the water will move laterally against the direction of the web-felt travel, and another part will pass through the midnip faster than the press speed. The hydraulic pressure varies along the nip, but is nearly constant through the thickness. In a practical press the flow pattern is more or less three-dimensional.

It is easy to see that the "midnip" dryness must increase with increasing pressure and freeness, and decrease with increasing speed. With transversal flow, an increase of basis weight will reduce the dryness, and with lateral flow, the dryness will be nearly independent of basis weight.

EXPANSION AND REWETTING

At or near the midnip, both web and felt or the felt alone begins to expand. In the initial expansion, either may remain saturated for some distance along the expanding nip. Immediately after that point, the felt becomes desaturated. The nip length is primarily governed by the resilience of the felt. When the felt cannot expand to fill the available gap, the point of web-felt separation is reached. A well-conditioned felt practically recovers all its original thickness. The web also undergoes desaturation. Since most paper is highly viscoelastic, it recovers only partially.

We have now come to the controversial aspect of "rewetting." For rewetting to occur, transfer of water from the felt to the paper must be originated by the action of expansion. An obvious process is due to capillary suction. Since the paper has a finer capillary structure than the felt, water will migrate into the paper across the interface from the felt. A second consideration arises from the dynamic suction generated in the initial expansion. The hydraulic pressure drops to the maximum suction, and then returns to the atmospheric pressure. As air can penetrate into the felt much more easily than the web, the latter has a longer suction zone, into which water tends to flow. A third possibility involves the separation of paper and felt. If a "film" of water exists in the interfacial layer, it must split into two parts under the stresses developed by the force of separation. Since the felt with a rougher texture contributes more water to the interface, the paper may gain water upon separation. More likely, however, is that the dynamic suction generated by the initial expansion of the felt draws water to the interface, which then migrates into the web under capillary suction.

All three mechanisms may be operative in the expanding nip. The dynamic suction zone occupies a fraction of the diverging nip. Next extends the main capillary suction zone until the incipience of interfacial split. A short separation zone then concludes the nip.

In this discussion, lateral flow of water in the web through the section of minimum moisture is not considered as rewetting. Lateral flow in the felt through the midnip, however, may be a potential source for rewetting.

The principal effects of the four operating variables on rewetting are summarized in Table I, neglecting their possible interactions.

TABLE I
REWETTING FACTORS

Zone	Increase of			
	Freeness	Basis Weight	Nip Pressure	Speed
Dynamic suction	+	-	o	+
Capillary suction	+	o	-	-
Film splitting	o	o	o	?

+ promotes rewetting
- reduces rewetting
o has little effect on rewetting.

COMPLICATING FACTORS

So far, we have focused our attention mostly to the paper. We now proceed to examine some additional factors which certainly introduce more complexity to the pressing system.

FELT

A moistened felt can serve as a water receptacle. A wet felt sooner or later reaches saturation. In a saturated state, the felt offers resistance to flow.

The structure of a felt can affect pressing considerably. In the compression phase, the woven base structure, especially yarn knuckles, introduces a periodic variation of nip pressure in both machine and cross-machine directions. Pressure nonuniformity reduces the overall effectiveness of compression.

In the expansion phase, the surface texture of a felt has a possible effect on rewetting. The coarser its texture, the more water can the felt provide at the interface, leading to a higher potential for rewetting.

PRESS

The three common types of wet presses differ primarily in the roll surface in contact with the felt. The roll surface may be smooth (plain press), grooved, or drilled (suction press). The effect of the roll surface on compression uniformity is summarized in Table II.

TABLE II
PRESS CHARACTERISTICS

<u>Press Type</u>	<u>Capacity for Water</u>	<u>Pressure</u>	<u>Flow</u>
Plain	None	Most uniform	Mostly lateral
Grooved	Moderate	Least uniform	Practically transversal
Suction	High	Less uniform	Largely transversal

Interfacial water as a source of rewetting is supplied from the roll grooves or holes and by lateral flow in the felt through the midnip.

SHADOW MARKING

In a suction press, the pressure is higher on the web and felt over the land than the open areas, resulting in different degrees of compression. Simultaneously, the lateral flow generated by high pressure gradients around the open area tends to realign the fibers over the land areas along the machine direction. The overall result is an optical pattern in the finished paper called shadow marking. This adverse effect may also be present in a grooved press at high loadings, or using lightweight felts.

CRUSHING

Transversal flow tends to stabilize, whereas lateral flow tends to disrupt the paper structure. As the lateral flow increases to a critical level, it begins to stretch the paper web immediately ahead of the nip. This is the incipience of crushing. At a higher loading, the distended web folds over into creases in the nip. If the loading is further increased, the web is fractured into small pieces. Crushing can happen in any press if a critical lateral flow is generated.

MATHEMATICAL MODELING

Theoretical analyses of wet pressing have had varying success so far. A mathematical model for a lateral-flow press initiated by Yih (1) and refined by Asklöf (2) and Wilder (3) appears to be basically valid. Transversal-flow press models, however, have not yielded reasonable results, and are being further pursued at the Institute and elsewhere. These models will be discussed in some detail to show their capabilities, as well as limitations. In addition, a simple model for rewetting will be presented.

LATERAL-FLOW PRESS

The lateral-flow press model basically describes the pressing of a saturated felt in a hard nip of two impermeable rolls. The lateral flow under the hydraulic pressure gradients developed by the nip loading is assumed to follow Darcy's law. The principal computer results of the Wilder model are summarized in a dimensionless form taken from the original paper:

$$s_e = 1 - \alpha + s(\alpha, \beta) \quad (1)$$

$$s_e = \frac{m W_f}{\rho h_i \epsilon_i}$$

$$\alpha = \frac{x_o^2}{r_o h_i \epsilon_i} = \frac{h_i - h_c}{h_i \epsilon_i}$$

$$\beta = \frac{x_o \mu k S^2}{\rho V} \left(\frac{1 - \epsilon_i}{\epsilon_i} \right)^2$$

where h = nip gap, cm

k = Kozeny constant, dimensionless

m = moisture/felt ratio, g/g

\underline{r} = radius, cm

\underline{s} = felt saturation expressed as a fraction of void volume
($\underline{s}_1 = 1$), dimensionless

\underline{x} = distance along nip, cm

\underline{S} = specific surface, surface area per unit volume of felt fibers,
 cm^2/cm^3

\underline{V} = felt or roll speed, cm/sec

\underline{W} = basis weight, g/cm^2

α = nip geometry parameter, dimensionless

β = permeability parameter, dimensionless

ϵ = felt porosity, dimensionless

μ = water viscosity, $\text{g}/\text{cm-sec}$

ρ = water density, g/cm^3

Subscripts:

\underline{c} = midnip

\underline{e} = nip exit

\underline{f} = felt

\underline{i} = nip inlet

\underline{o} = roll; origin of \underline{x} at midnip

By definition, α is simply the fraction of water removed in the half nip length \underline{x}_o . Therefore, Equation (1) states that the exit moisture is equal to the midnip moisture, plus the extra moisture due to lateral flow through the midnip. The function, $\underline{s}(\alpha, \beta)$, representing the extra moisture, is a significant correction, and practically independent of β , as shown in Table III cited from the original paper.

TABLE III
 $\underline{s}(\alpha, \beta)$ FOR HARD NIP

β	α				
	0.1	0.3	0.4	0.5	0.7
10	0.044	0.088	0.099	0.100	0.081
30	0.042	0.083	0.093	0.096	0.079
100	0.041	0.081	0.091	0.094	0.078
300	0.040	0.080	0.091	0.094	0.078

The extension of this model to a deformable nip shows that the correction remains about the same.

TRANSVERSAL-FLOW PRESS

At present, we suggest simplified models for the dynamics of wet pressing in a transversal-flow press. These models, as developed in the appendix, are expressed in a dimensionless form:

$$m_e = m_c + m_r \quad (2)$$

$$(m_i^2 - m_c^2) + \frac{2\rho}{\rho_f} (m_i - m_c) \approx \frac{2\rho^2 \bar{K} F}{\mu W^2 V} \quad (3)$$

$$m_r = \frac{R}{W} = \left(\frac{2\rho^2 K_s p_s x_o}{\mu W^2 V} \right)^{1/2} \quad (4)$$

where \underline{m} = moisture/paper ratio, g/g
 \underline{x} = distance along nip, cm
 \underline{p} = hydraulic pressure, dyne/cm²
 \underline{F} = nip loading, dyne/cm
 \underline{K} = permeability of paper, cm²
 \underline{R} = specific rewetting, g/cm²

\underline{V} = roll speed, cm/sec

\underline{W} = basis weight of paper, g/cm²

μ = viscosity, g/cm-sec

ρ = density, g/cm³

Subscripts:

\underline{c} = midnip

\underline{e} = nip exit

\underline{f} = fiber

\underline{i} = nip inlet

\underline{o} = origin of \underline{x} at midnip

\underline{r} = rewetting

\underline{s} = capillary suction

In Equation (3), $2\rho^2\bar{K}\underline{F}/\mu\underline{W}^2\underline{V}$, indicates the dependence of flow in flow-controlled compression on the nondimensional combination of the six variables. The average permeability \bar{K} , is independent of the water properties, ρ and μ , but dependent on the operating variables, \underline{F} , \underline{V} , and \underline{W} , because the interaction of flow and compression has not been taken into account. \bar{K} , therefore, cannot be determined separately from the nip dynamics. In this respect, the model for compression has no quantitative predictive power. It merely shows the direction of change upon changing each of these variables.

The model for rewetting is

$$R = \left(\frac{2\rho^2 K_s p_s x_o}{\mu V} \right)^{1/2}$$

This expression implies that specific rewetting, \underline{R} , is independent of basis weight. The reabsorbed moisture, \underline{m}_r , is simply equal to $\underline{R}/\underline{W}$. It is noted that \underline{R} is inversely proportional to $\sqrt{\underline{V}}$. Rewetting becomes insignificant at very

high speeds or short times. In this model the interfacial water for rewetting is assumed to be supplied by the initial expansion of the felt, and film splitting is not considered.

Capillary pressure is an inverse function of pore size. The texture of a felt is generally much more coarse than paper. Hence, capillary suction is controlled by paper. The capillary pressure of paper is generated by desaturation in its initial recovery. After the initial recovery, the web is assumed to attain a practically constant thickness along the remaining nip, during which both capillary pressure and permeability are considered to remain constant.

EXPERIMENTAL EVIDENCE

Wilder has checked the lateral-flow press model for the pressing of a saturated felt in a hard nip against the data of Huyck Corporation. Figure 1 shows the agreement of the model with the Huyck data for one felt (1). The average deviation is about 6%. With the guidance of this model, we can extract some useful information from the available data.

NIP GEOMETRY

The original data involve the following measurements: \underline{r}_0 , \underline{F} , \underline{V} , \underline{h}_i , \underline{h}_c , and \underline{m}_e , from which \underline{W}_f is derived to be 0.109 g/cm², and ϵ_i is estimated to be 0.7. Since the model implies that the dynamic half nip length, \underline{x}_0 , is dependent on the nip loading, \underline{F} , and the felt speed, \underline{V} , we seek such a correlation for the particular felt. By trial and error, the following correlation, as shown in Fig. 2, appears to be satisfactory:

$$\underline{x}_0 = 0.06 (F/V^{0.2})^{0.2} \text{ in cgs units} \quad (5)$$

This correlation is inapplicable to low speeds at which the nip length should approach the static value:

$$\underline{x}_0 = [r_0(h_i - h_c)]^{1/2} \quad (6)$$

where \underline{h}_c is a function of compacting pressure only.

FELT COMPRESSIBILITY

The nip geometry parameter also represents the compressibility factor. The static compressibility of a fiber mat is known to contain the elastic modulus of fiber (4). It seems reasonable to assume the modulus of the fiber or yarn as a parameter in the dynamic compressibility of the felt. The diameter, spacing,

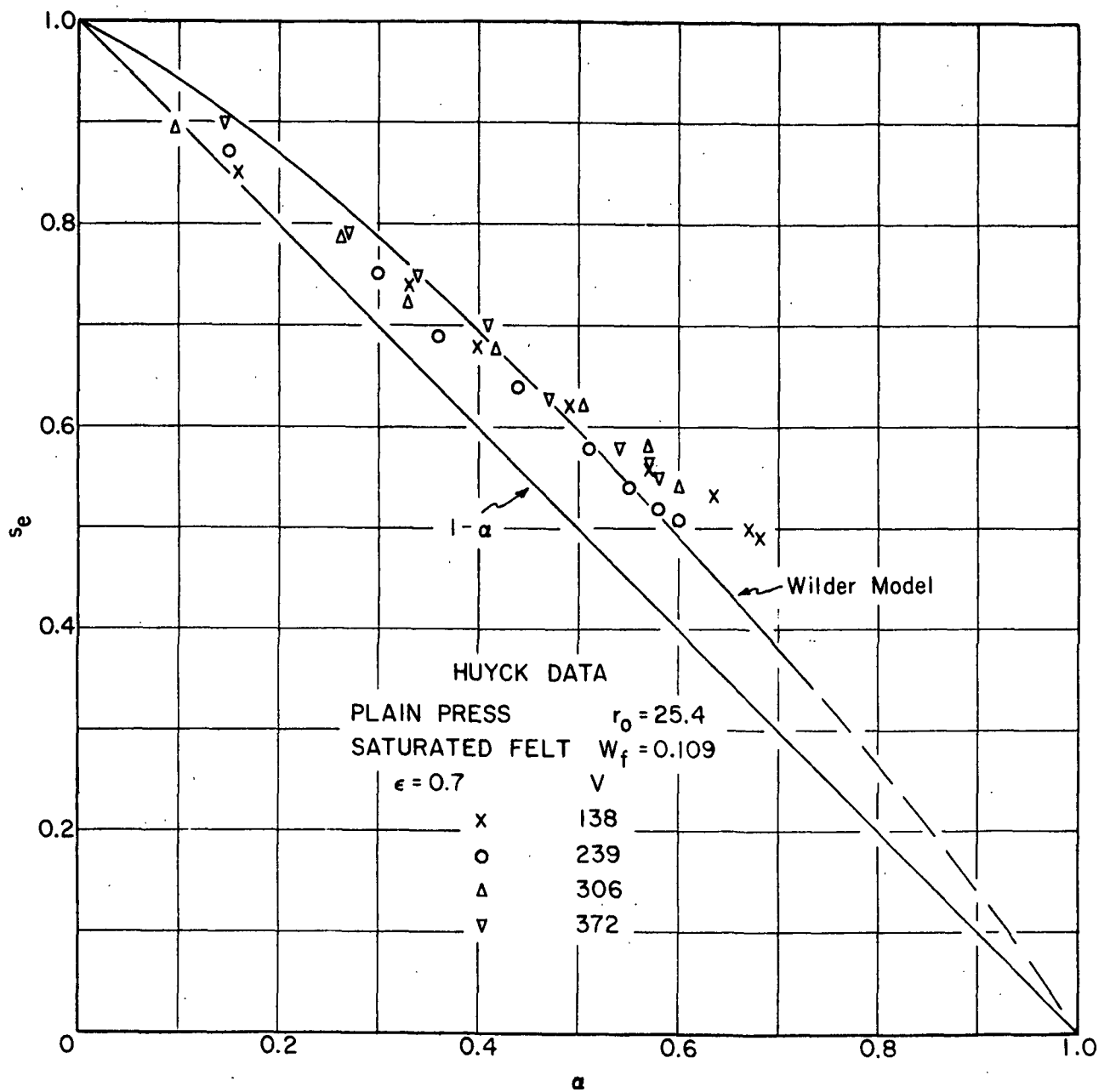


Figure 1. Experimental Verification of the Lateral-Flow Press Model

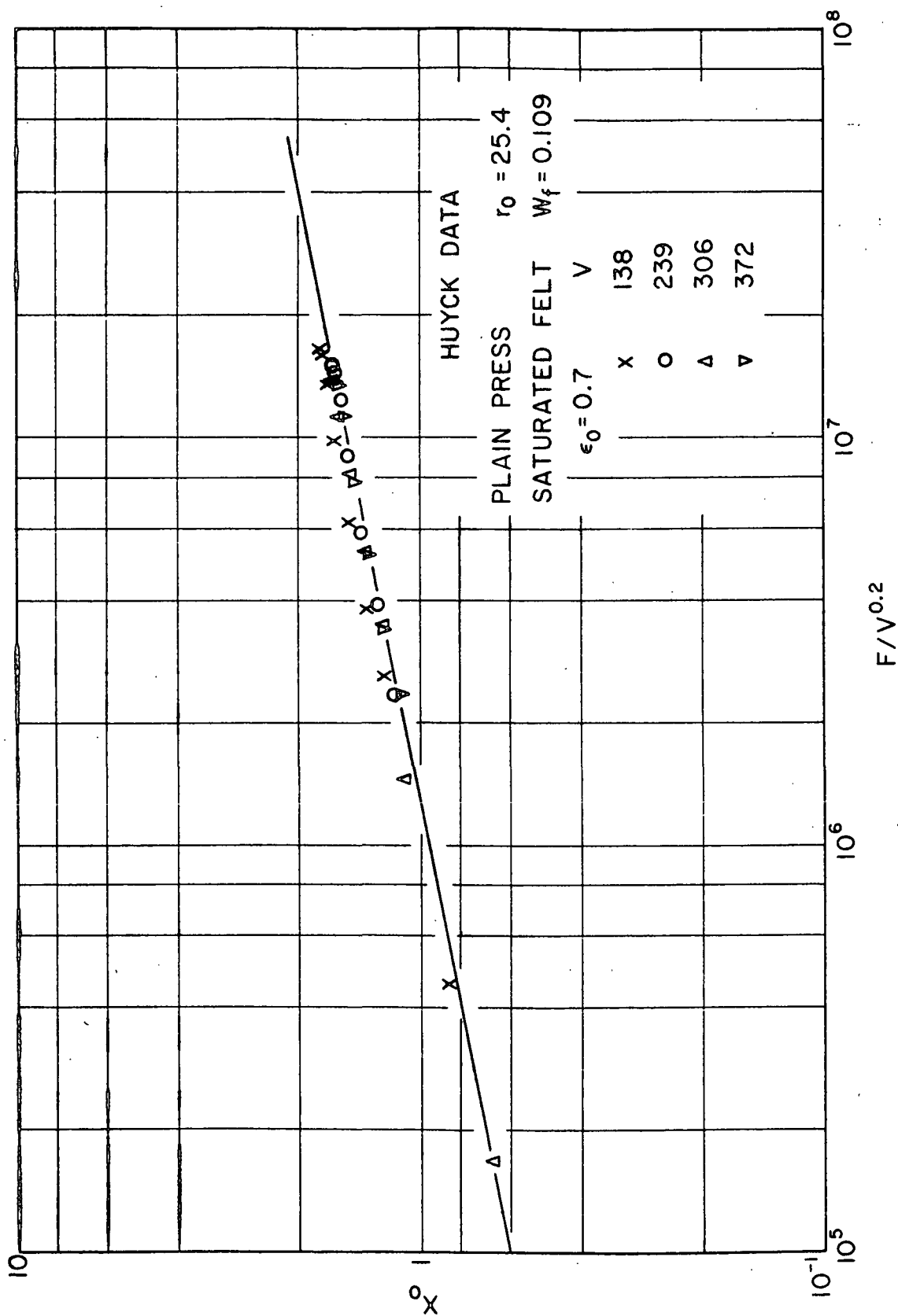


Figure 2. Dependence of Nip Length on Loading and Speed

and crimp of the yarns must have some effect on compression uniformity in addition to the felt compressibility.

The concept of nip geometry or dynamic compressibility may be extended to other types of press. Recent experiments conducted at Appleton Mills under controlled conditions (5) serve to demonstrate this point. Figure 3 shows a single correlation for two felts of a similar design pressed in a plain and a grooved hard nip. It is seen that the nip length is closely the same at the same loading in spite of the difference in felt basis weight and roll surface.

LOAD LIMIT

The upper limit in nip loading is the fiber density. For the felt referred to in Fig. 3, the average fiber density is about 1.2 g/cm^3 . The midnip gap corresponding to this density is 0.061 cm at a basis weight of 0.073 g/cm^2 . The uncompressed felt thickness is 0.224 cm , and the roll radius, 7.6 cm ; therefore, the half nip length is approximately 1.1 cm . Extrapolation of the correlation yields a loading of $2 \times 10^8 \text{ dyne/cm}$ (1000 pli), representing the limit at 635 cm/sec (1250 fpm). In the plain press, crushing occurs long before this loading is reached; in the grooved press, a large part of the nip becomes ineffective for water removal at such a high load.

PEAK PRESSURE

The pressure profile along a hard nip may be approximated by a trigonometric function such as

$$P = P_c \cos \left(\frac{\pi x}{2 x_o} \right), \quad -x_o \leq x \leq 0 \quad (7)$$

where P is the mechanical pressure due to loading. The average pressure is then

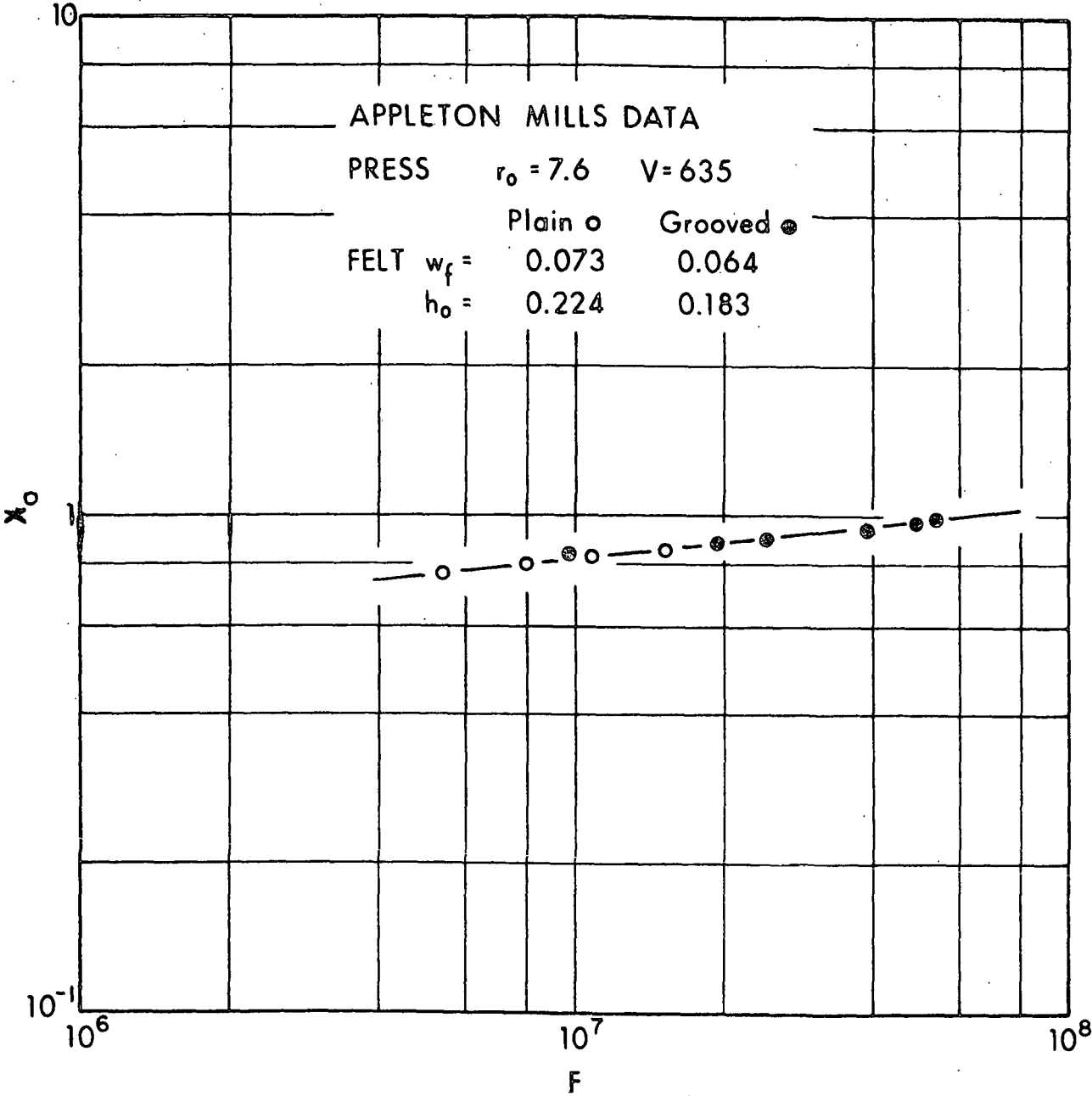


Figure 3. Nip Length in Plain and Grooved Presses

$$\bar{P} = P_c \int_{-1}^0 \cos\left(\frac{\pi x}{2 x_o}\right) d\left(\frac{x}{x_o}\right) = \frac{2}{\pi} P_c \quad (8)$$

and the peak pressure is related to the loading by

$$P_c = \frac{\pi}{2} \bar{P} = \frac{\pi}{4} \frac{F}{x_o} \quad (9)$$

PAPER COMPRESSIBILITY

The dynamic compressibility of paper in a plain press with a hard nip must be dependent on the pressure profile which is controlled by the felt compressibility. We would expect a correlation for compression of paper such as

$$\frac{H_c}{W} = \frac{m_c}{\rho} + \frac{1}{\rho_f} = M P_c^{-m} t_c^{-n} \quad (10)$$

where $\underline{H_c}$ is the thickness of paper at the peak pressure, and $\underline{t_c}$, the duration of compression ($\underline{t_c} = \underline{x_o}/V$).

The data of Appleton Mills for pressing unrefined northern softwood bleached kraft and glassine handsheets with a woolen felt (A) and a batt-on-mesh synthetic fiber felt (B) in a plain press with a hard nip are so correlated in Fig. 4 and 5 under the assumption: $\underline{m_c} \propto \underline{m_e}$. The correlation in Fig. 4 shows that the apparent density of the paper at constant loading is inversely proportional to $\underline{V}^{0.08}$ irrespective of the furnish and the felt. It appears that the time-dependent deformation of cellulose fibers remains unchanged in spite of refining. The level of density for the same paper depends on the felt. The effect of the felt structure is primarily one of compression uniformity. Since Felt A has a more uniform structure than Felt B, the former leads to more effective compression. The effect of the two felts is the same on both kraft and glassine, independent of speed. With the same felt, the identical load yields

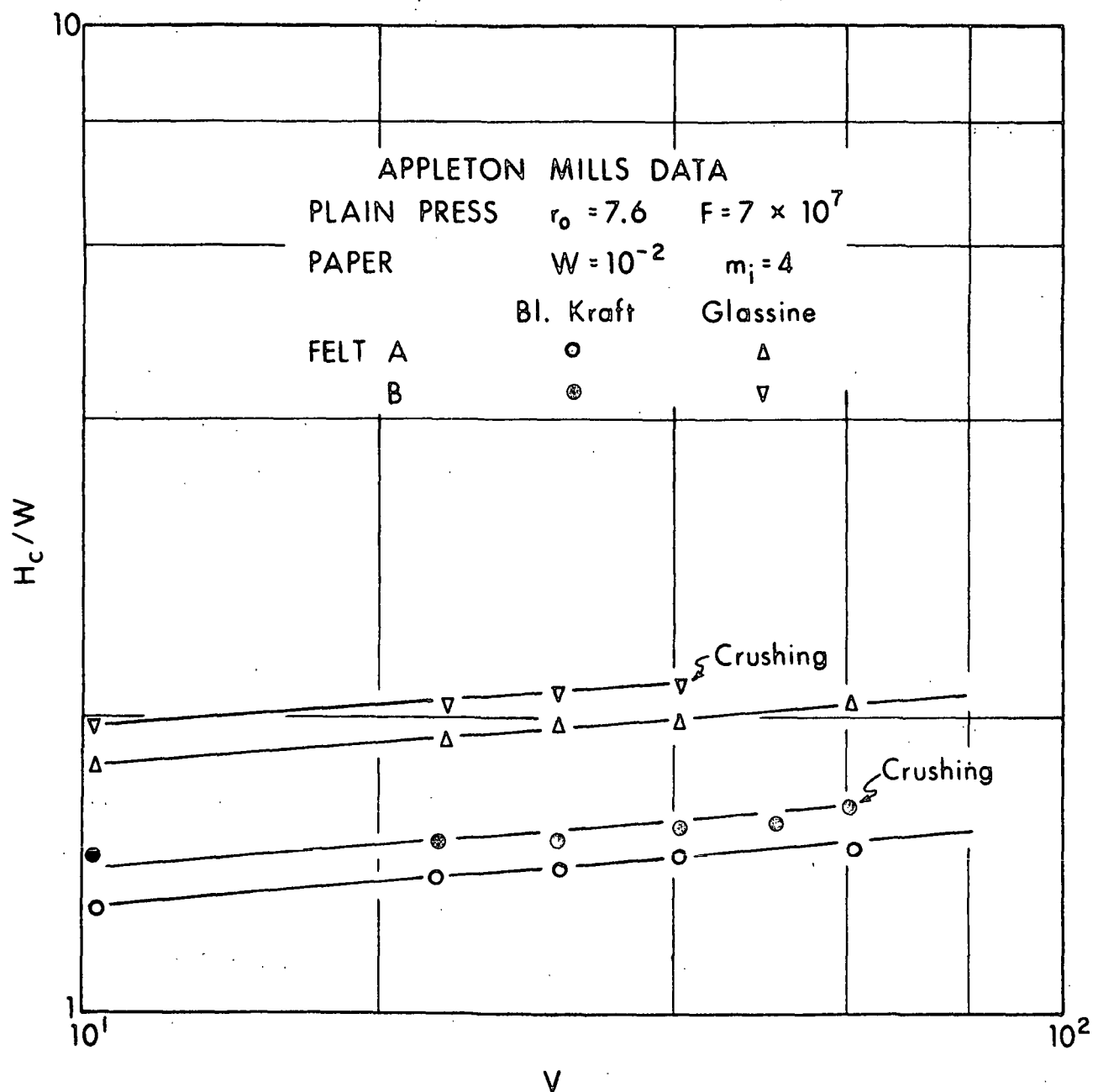


Figure 4. Compression of Paper in a Plain Press

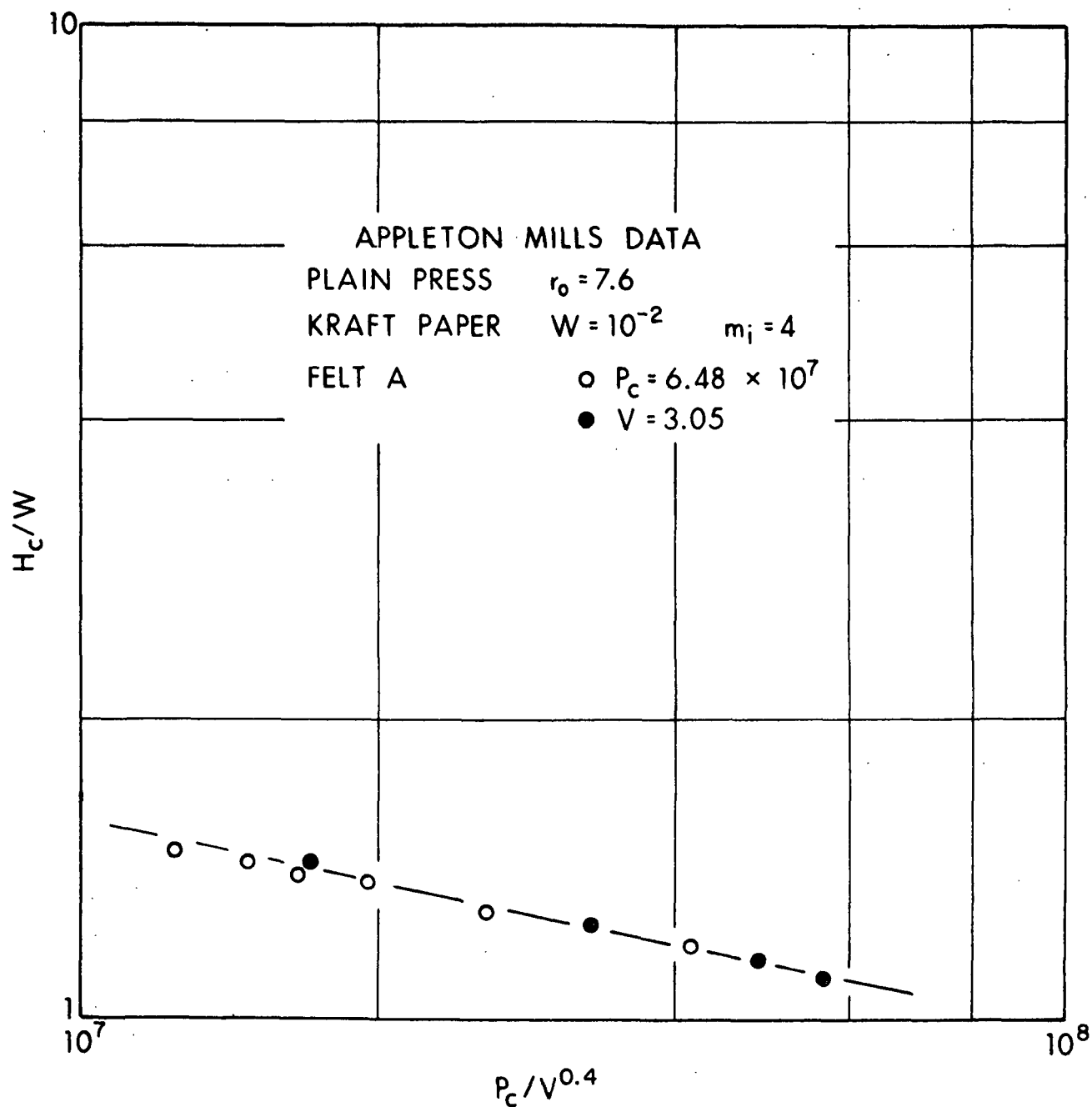


Figure 5. Dynamic Compressibility of Paper in a Plain Press

a lower density for glassine, indicating the effect of the paper compressibility, and, to some extent, that of its permeability.

Figure 5 correlates the reciprocal of density with both $\underline{P_c}$ and \underline{V} for the same kraft paper pressed with the same Felt A. The correlation is

$$\frac{H}{W} = 40 (P_c/V^{0.4})^{-0.2} \text{ in cgs units} \quad (11)$$

The power 0.2 is in the range of \underline{N} in the static compressibility function, $\underline{W/H_c} = \underline{MP}^{\underline{N}}$, for unrefined northern softwood bleached kraft. If the dynamic compressibility function of the felt is known, the exit moisture of the paper can be expressed in terms of \underline{F} and \underline{V} .

BASIS WEIGHT

If the flow is lateral, the compressibility of paper should be practically independent of basis weight. Additional data of Appleton Mills, as shown in Fig. 6, however, reveal somewhat more complicated effects. With Felt A of a more uniform structure, the slight increase of paper moisture for both kraft and glassine with increasing basis weight is attributable to transversal flow in the early part of the nip prior to the saturation of the felt. The much higher moisture of glassine than that of kraft at the same basis weight is due to the much lower permeability of glassine.

With Felt B, the effect of nonuniform compression is more pronounced than with Felt A. The paper dryness increases at first with increasing basis weight because a thicker sheet tends to homogenize the nonuniform pressure arising from the felt structure. Nevertheless, the small effect of transversal flow also exists. As the basis weight is further increased, the paper sooner

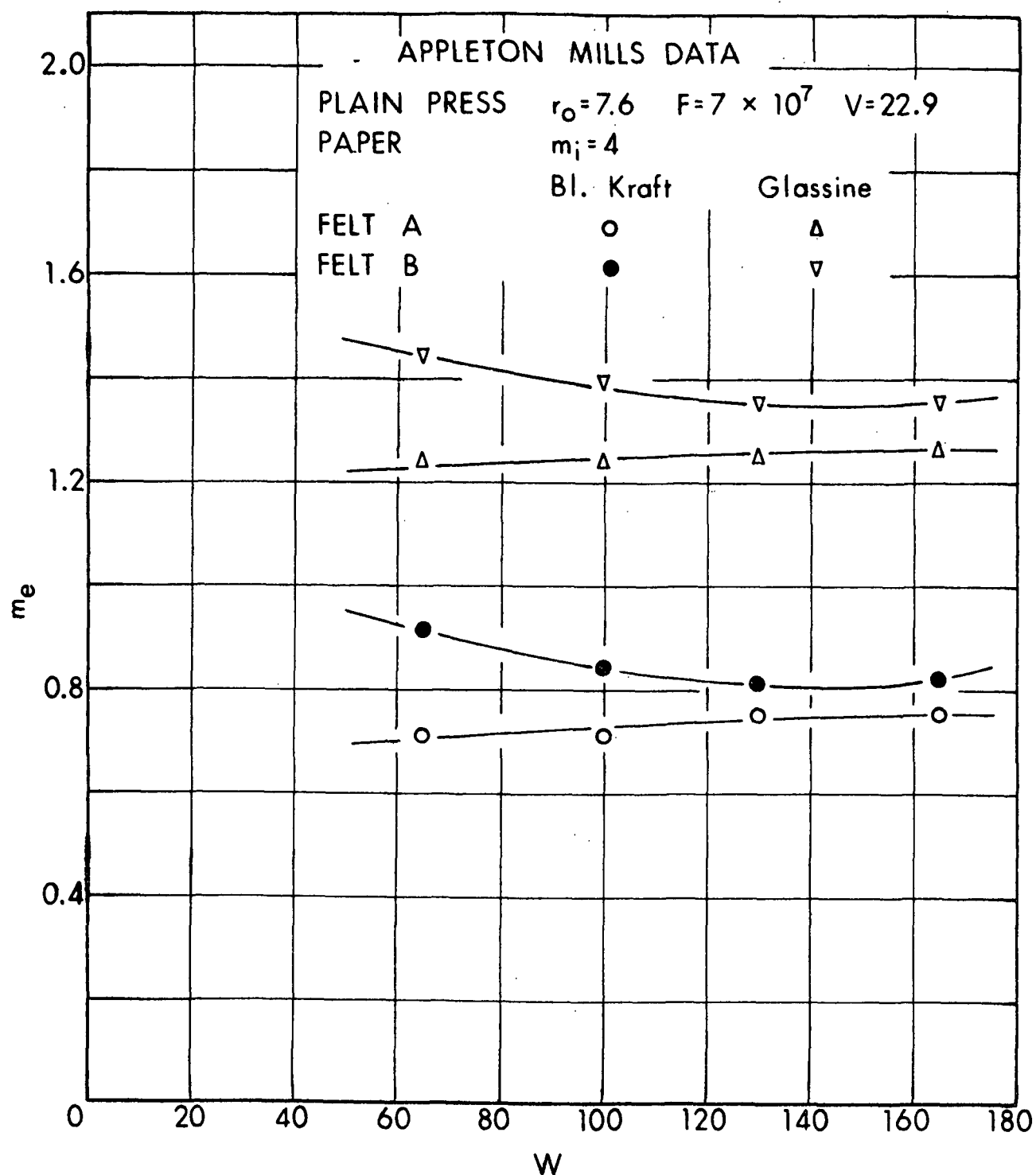


Figure 6. Effects of Basis Weight in a Plain Press

or later attains a minimum moisture or maximum dryness due to the combination of the two opposing factors.

REWETTING

Appleton Mills also supplied a set of data for the exit moisture of the same kraft paper pressed in a plain vs. grooved hard nip at low speeds. In these experiments, the loading on the plain press was adjusted to give the same apparent pressure as that over the land area in the grooved press. Felt B was used in both presses. The comparison is shown in Fig. 7. The dramatic difference of the exit moisture at very low speeds may be attributed largely to rewetting. In the foregoing analysis of the plain press data, rewetting has been assumed to be insignificant. For the grooved press, it is possible to estimate the maximum extent of rewetting which may have occurred. The static compressibility of a similar kraft wet mat indicated a density ($\frac{W}{H_c}$) of about 1 g/cm³ at the applied pressure of 10⁸ dyne/cm². The cellulose fiber density being about 1.5, the moisture of the mat is about 0.33 g/g. This represents the lowest moisture of the kraft paper attainable in the grooved press. Then the maximum rewetting, R, would be around 10⁻² g/cm² at 3 cm/sec.

The proposed rewetting model has been verified with a single set of unpublished data to the extent that R is inversely proportional to \sqrt{V} . With this evidence, a hypothetical rewetting line for the grooved press is shown in Fig. 7. By deducting the reabsorbed moisture from the data, the minimum moisture at the midnip at all speeds may be reconstituted as shown. The resulting curve is reasonable as it exhibits a monotonic increase with speed in accordance with the compression model, rather than passing through a minimum indicated by the original data. At a speed of 10³ cm/sec, rewetting for this kraft paper would be relatively small.

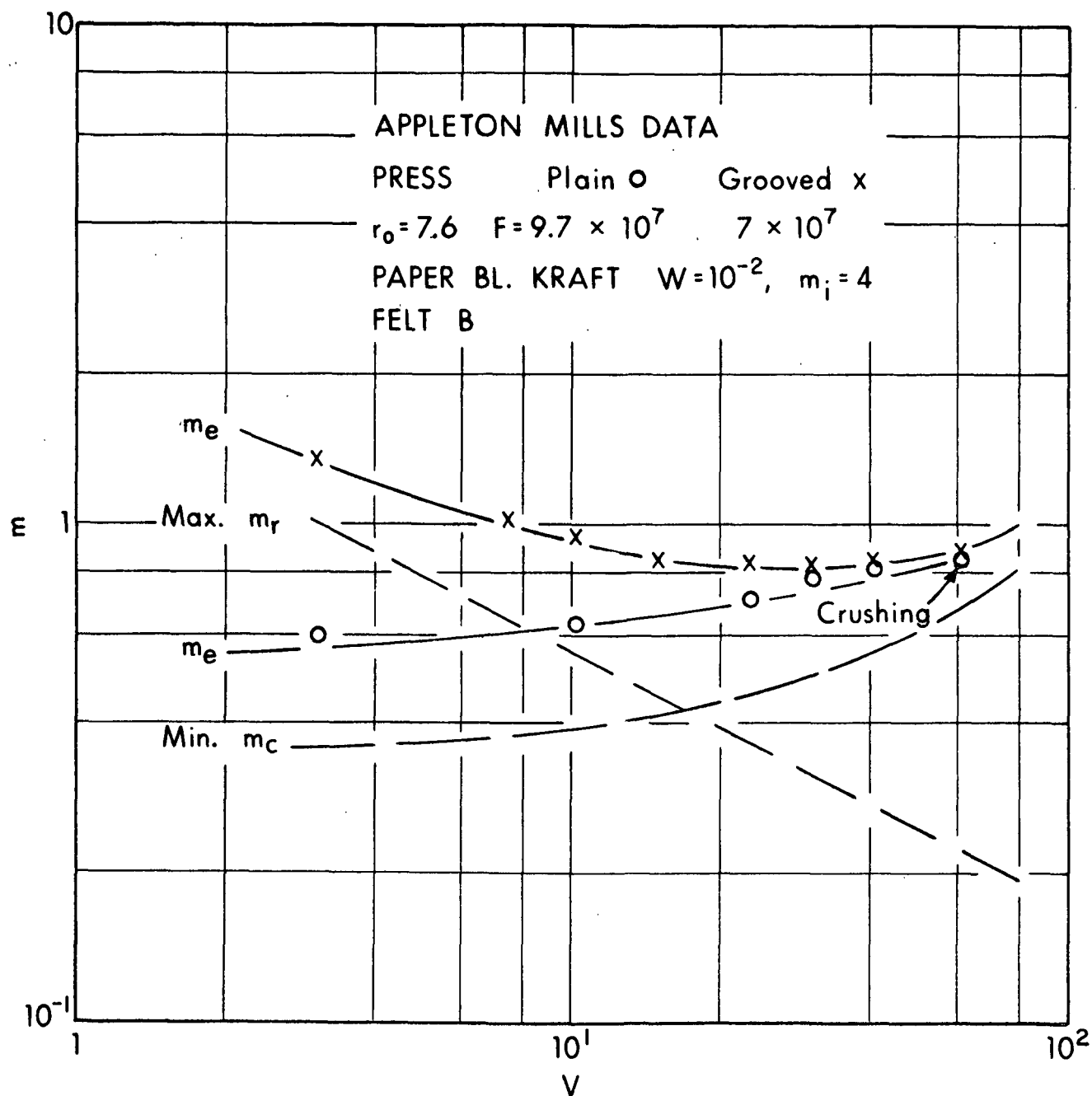


Figure 7. Rewetting in a Grooved Press

The reconstituted midnip moisture curve for the grooved press is substantially lower than the data for the plain press. This is largely due to the maximum correction for possible rewetting in the grooved press, and partly because of the lateral flow through the midnip in the plain press, as well as some transversal flow and rewetting which may also have occurred in the plain press.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

1. In any common type of press, the nip length is largely determined by the felt compressibility. The dynamic compressibility of a felt can be measured experimentally, and correlated in terms of loading and speed.
2. In a lateral-flow press, the final dryness of paper is governed by the compressibility of both paper and felt, with some correction for the lateral flow through the midnip.
3. In a transversal-flow press, the final dryness is controlled by the flow-compression interaction at high speeds and by rewetting at low speeds.
4. Increasing nip loading yields diminishing returns.
5. Increasing nip length promotes compression.
6. Increasing speed reduces rewetting.
7. Improving uniformity of compression enhances dryness.

RECOMMENDATIONS

1. To develop a single-press system for most common grades of paper and board. An ideal system would consist of a plain press with an extended nip at moderate loading and a conventional felt wringer at heavier loading, with a uniform felt serving as a water receptacle for transversal flow in the long nip.
2. To extend the characterization of a felt in terms of the felt structure and fiber properties. Yarn size, spacing, and crimp, as well as fiber

modulus, diameter, density, and twist are some of the factors to be taken into account.

3. To complete a mathematical model for transversal-flow compression. It should have the power of predicting moisture profiles in both machine and thickness directions.

4. To obtain information and to generalize correlations for compressibility, recovery, and permeability of paper. Fiber deswelling and contact area development are two important factors to be clarified.

The Institute is presently engaged in the research of the last two aspects under the "wet pressing" project.

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APPENDIX

DEVELOPMENT OF SIMPLIFIED WET PRESSING MODELS

FLOW-CONTROLLED COMPRESSION

Slow flow through a uniform fiber mat follows Darcy's law:

$$U = \frac{K}{\mu} \frac{\Delta p}{H} \quad (12)$$

\underline{U} is the superficial velocity (volumetric flow rate per unit area of the mat), and Δp , the hydraulic pressure drop across the mat of thickness \underline{H} . \underline{K} is the permeability, and μ the viscosity of water.

Consider the compression of a water-saturated fiber mat against a wet felt under constant pressure. At any instant during compression, the rate of thickness change is equal to \underline{U} , and the applied pressure is equal to Δp by setting atmospheric pressure to zero. We then have

$$-\frac{dH}{dt} = \frac{K}{\mu} p \quad (13)$$

Integrating for the time of compression, $\underline{t_c}$,

$$(H_i^2 - H_c^2) = \frac{2p}{\mu} \int_0^{t_c} K dt = \frac{2\bar{K} p t_c}{\mu} \quad (14)$$

Since, for a saturated mat,

$$\frac{H}{W} = \frac{m}{\rho} + \frac{1}{\rho_f} \quad (15)$$

where \underline{m} is the moisture/fiber ratio, \underline{W} the basis weight, ρ the water density, and ρ_f the fiber density, we have

$$(m_i^2 - m_c^2) + \frac{2\rho}{\rho_f} (m_i - m_c) = \frac{2\rho^2 \bar{K} p t_c}{\mu W^2} \quad (16)$$

CAPILLARY-CONTROLLED REWETTING

Upon release of pressure, the mat recovers instantaneously to a fraction of H_i , and generates a capillary pressure p_s by desaturation. A continuous water network is supposed to exist at the paper-felt interface, and this "film" of water moves into the paper at constant p_s . Using Darcy's law and expressing the instantaneous film thickness in terms of the specific rewetting R/ρ , we arrive at an expression similar to Equation (13):

$$\frac{dR}{dt} = \frac{\rho^2 K_s p_s}{\mu R} \quad (17)$$

and

$$R = \left[\frac{2\rho^2 K_s p_s t_e}{\mu} \right]^{1/2} \quad (18)$$

where t_e is the time from the pressure release to the separation of the paper and felt, and K_s , the permeability of the paper.

APPLICATION TO A PRESS

In a press nip,

$$t_c = t_e = x_o/V$$

and

$$p \propto F/x_o$$

where x_o is the half nip length, V the speed, and F the linear loading.

The models then are:

$$(m_i^2 - m_c^2) + \frac{2\rho}{\rho_f} (m_i - m_c) \cong \frac{2\rho^2 K F}{\mu W^2 V} \quad (19)$$

$$m_r = \frac{R}{W} = \left[\frac{2\rho^2 K_s p_s x_o}{\mu W^2 V} \right]^{1/2} \quad (20)$$

$$m_e = m_c + m_r \quad (21)$$

